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The effect of islands' interconnection to the mainland system on the development of renewable energy sources in the Greek power sector

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ABSTRACT

The capacity expansion planning is a crucial process taking into account multiple aspects and various parameters of the examined power sector in order to optimally satisfy the future electricity demand. In the case of Greece, the long-term energy planning of the electricity supply sector faces a lot of challenges deriving from the peculiarities and geomorphology of the country mainly referring to the large number of islands. This paper explores the feasibility and the consequences of interconnecting Greek islands to the mainland grid by establishing two alternative scenarios of least cost electricity planning for the period 2009–2020. Namely, the reference scenario assumes isolated electric systems of islands and is compared against the alternative option of their interconnection to the mainland. The main purpose of the present study is to illustrate the great importance of islands' interconnection on the development of renewable energy sources (RES) to generate electricity while pointing out the consequent economic and environmental benefits.

Contents

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1. Introduction

Electricity corresponds to the most widespread form of energy while being the fundamental commodity to everyday's social and economic activities across the entire world. The power sector represents the core element of the electricity's energy chain and comprises all the production units used to transform energy and produce power through either physical or chemical processes.

Historically, the power sector is based on fossil fuels like oil, coal and natural gas while in some countries electricity originates from the utilization of nuclear energy. The increasing and severe environmental problems arisen and caused by the conventional ways of power generation, along with the depletion of fossil fuel reserves gave the opportunity to renewable energy sources (RES) to appear as an alternative, trustworthy and sustainable mean to produce electricity. During the last decade, RES started to play an increasingly important role and to increase their share in many countries' electricity mix. Nowadays their huge potential is widely recognized as a decisive factor to satisfy the continuously growing demand while at the same time mitigating severe environmental problems like climate change, acid rain, ground erosion etc. Wind and hydropower possess actually the most prominent position in the electricity sector followed by other forms of RES like biomass, solar etc.

The multiplicity of technological solutions implies that the electricity supply industry (ESI) has to satisfy the increasing demand by taking difficult investment and operational decisions. Besides its economic profitability and viability, major concerns are the protection of environment and the fulfillment of various commitments and obligations under national and international treaties. Furthermore, electric utilities have to adapt to the sociopolitical situation in each country, as well as to the particular conditions of each electricity system.

Therefore, the power sector performs into a manifold canvas composed by economic, technological, political, environmental and social hues facing a lot of problems and challenges to respond. The application of energy planning is a necessary condition to manage electricity demand and supply and ensure the effective operation of the electricity supply sector. Usually, it is categorized in short-term, medium-term and long-term energy planning. In this paper, we are interested in long-term energy planning for the electricity system which is also referred as capacity expansion planning and or least cost electricity planning.

Capacity expansion planning is occupied with four major queries concerning the investment decisions about power units [1–3]:

- ***what***, corresponding to the choice of technologies to produce power
- ***how***, meaning the number, the size and the capacity of future power plants
- ***when***, the time to build new installations and to retire old ones
- ***where***, the location to install new power plants

Least cost electricity planning tries to answer these questions and to designate the appropriate strategies to manage and expand the power sector. As implied by the term 'least cost', the aim is the satisfaction of consumers' electricity needs through the minimization of total cost of investment and operation of power units. In the past, cost minimization was the unique criterion to decide on energy planning. After 80's the introduction of environmental dimension altered this consideration and a multicriterion perspective was adopted [4]. It was the increasing concern about the greenhouse effect and the consequences of global warming that triggered the international social and political interest to institute new and stricter legislations with specific commitments for the power sector which has a large share on total emissions. Environment has been upgraded to a very significant parameter in designing future capacity expansion strategies consolidating the triptych of energy, economy and environment.

In many energy problems, environment is introduced either as constraint or as additional criterion (or objective) giving the importance of mitigating pollution effects but also is often embedded as an economic parameter through the internalization of penalties and external environmental costs [5]. Such example is the purchase of greenhouse gases (GHG) emissions rights which is mandatory for electric utilities in the European Union (EU) and it is incorporated into the total cost of generating electricity.

The long-term energy planning of a country's power sector is usually implemented by appropriate energy models. Energy models provide the methodological framework to simulate and optimize energy systems and guide to the solution of a sustainable capacity expansion planning.

The present paper considers all above aspects and implements energy planning in the Greek power sector by developing and using an optimization energy model. The main scope of this paper is to investigate the effect of interconnecting Greek islands to the mainland system via electric submarine cables. The islands' interconnection is a crucial issue that has been examined many times in the past but never really advanced. The starting point was the possible interconnection of Cyclades which has been debated and explored at the end of 1980 from Public Power Company (PPC) but soon postponed due to the citizens' opposition. The concern about Cyclades emerged again in 2004 and a relative study was prepared for Regulatory Authority for Energy by National Technical University of Athens [6] confirming their interconnection as a highly beneficial project, from both the economic and social point of view. The Cyclades project was included in the development programme of the Greek transmission system and PPC was assigned to implement the designated interconnection up to 2010 but still nothing has implemented. Similar attempts and plans have been elaborated from private power companies that wanted to undertake the cost of islands' interconnection in order to install large wind farms and exploit the existing huge wind potential specifically in Cyclades and Northern Aegean islands. Recently, in 2006, alternative options to install submarine cables and interconnect the majority of Greek islands by grouping them per geographical proximity have been systematically studied [7].

Nevertheless, all these attempts did not succeed to promote the interconnection of Greek islands to the mainland, despite the prospective economic, social and environmental benefits. The challenge continues to be extremely essential and the islands' interconnection should be subsumed to the long-term energy planning of the whole power sector. The interconnection project is a capital intensive investment and a fundamental intervention in Greek electricity system and has to be considered at a strategic level in order to make a right pre-assessment and reveal its far-sighted and sustainable benefits for the insular regions and the whole country.

Considering the great potential of Greece on RES, this study attempts to show the positive effects and the reinforcing role that the interconnection of Greek islands can play on further RES development. For this reason, we developed two scenarios, a reference case without the option of interconnection and a second scenario giving this possibility in order to compare the power sector's behavior towards RES promotion.

The remainder of the paper has the following structure. After this detailed introductory section, the current status of Greek power sector is presented by giving emphasis to its main problems and obligations and by analyzing the challenging topic of islands' interconnection. In Section 3, the adopted methodological approach and the developed energy model are described. Section 4 presents synoptically data and main assumptions used in the

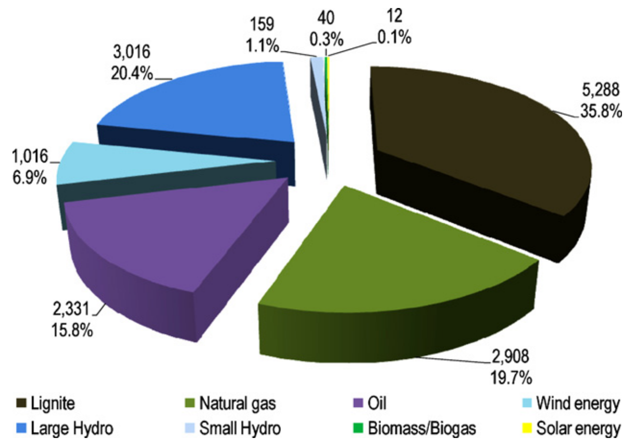

Fig. 1. Mix of installed power capacity in 2008 (MW).

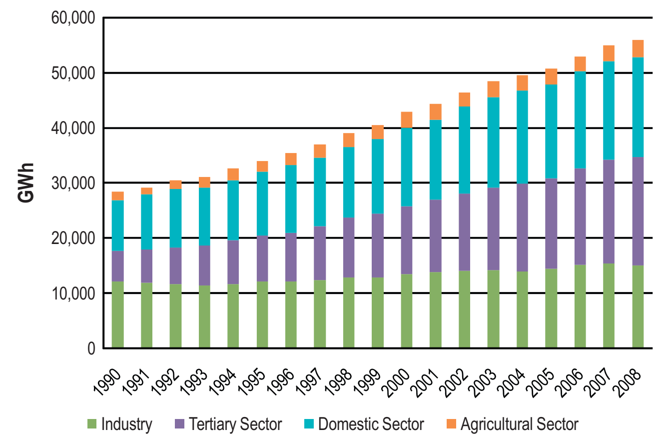

Fig. 3. Evolution of electricity consumption per sector [9].

energy model. Section 5 depicts the two scenarios developed and discusses the results obtained from the optimization of the energy model. The main findings and the conclusions of this study are summarized in the last section.

2. The Greek power sector

2.1. Structure

Greece is a Mediterranean country and has one of the longest coastlines mainly because of the large number of its islands. Due to this special geomorphology, the Greek power sector consists of two discrete subsystems, the main interconnected electric grid that covers the mainland and the isolated power systems of Aegean islands.

In total, the Greek power system has 14.8 GW of installed capacity. Lignite power stations correspond to 5.3 GW and natural gas power plants to 2.9 GW (see Fig. 1). Hydroelectric stations are summing up to 3 GW while small hydropower plants do not exceed 160 MW. The installed capacity of wind parks reaches 1 GW in 2008 of which 791 MW are installed in mainland while the rest 225 MW in insular system, with the great majority being located in Crete.

The mainland power system is dominated by the intensive use of lignite which has long been the national energy resource and the cornerstone of electricity generation (see Fig. 2). During the last decade, natural gas started to play an important role in the power mix covering mostly peak power loads due to its high price. Concerning RES, wind energy shows the largest incremental trend, but its penetration is still very low compared to the high wind potential of Greece and the rates observed in other European countries. Photovoltaic (PV) installations, being the most widespread solar technology, still present a very low share in the power mix. Large hydropower plants contribute up to their maximum potential as their operation is constrained by the long lasting scarcity of water. In 2008, RES produced a small amount of electricity accumulating just 5.6 TWh (including large hydro) corresponding to a share of 9.1%.

Despite the great RES potential of Greek islands, their electricity needs are covered almost exclusively by heavy fuel oil (HFO) and light fuel oil (LFO) which are expected to continue dominating the autonomous insular systems in the future, unless the anticipating interconnection to the mainland advances.

In Greece, the electricity demand has shown an impressive upward trend especially after 1990, reaching 55.9 TWh in 2008. The domestic and tertiary sectors are the largest consumers and the main contributors to this remarkable growth as seen in Fig. 3.

2.2. National obligations and targets

Greece as a member of EU and Annex-I party of the Kyoto Protocol (KP) is obliged to constrain the increase of GHG emissions up to 25% for the 1st commitment period (2008–2012) in relation to

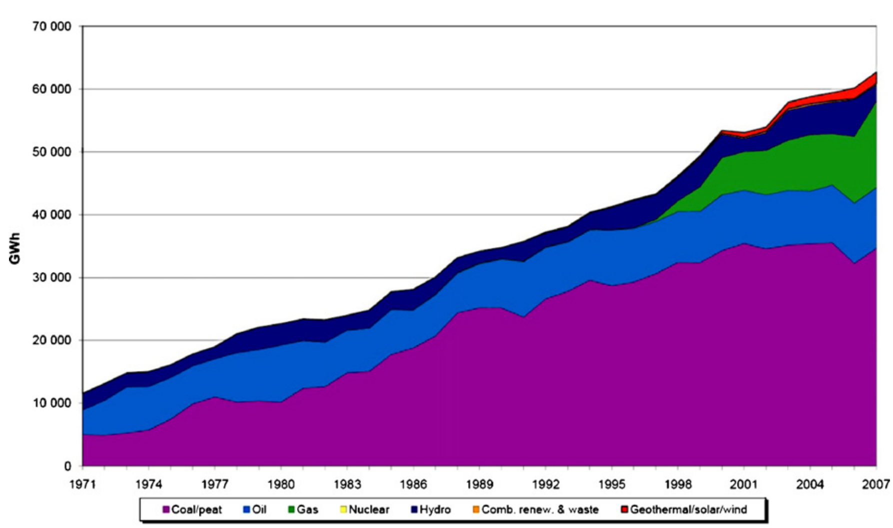

Fig. 2. The evolution of gross electricity generation per energy source [8].

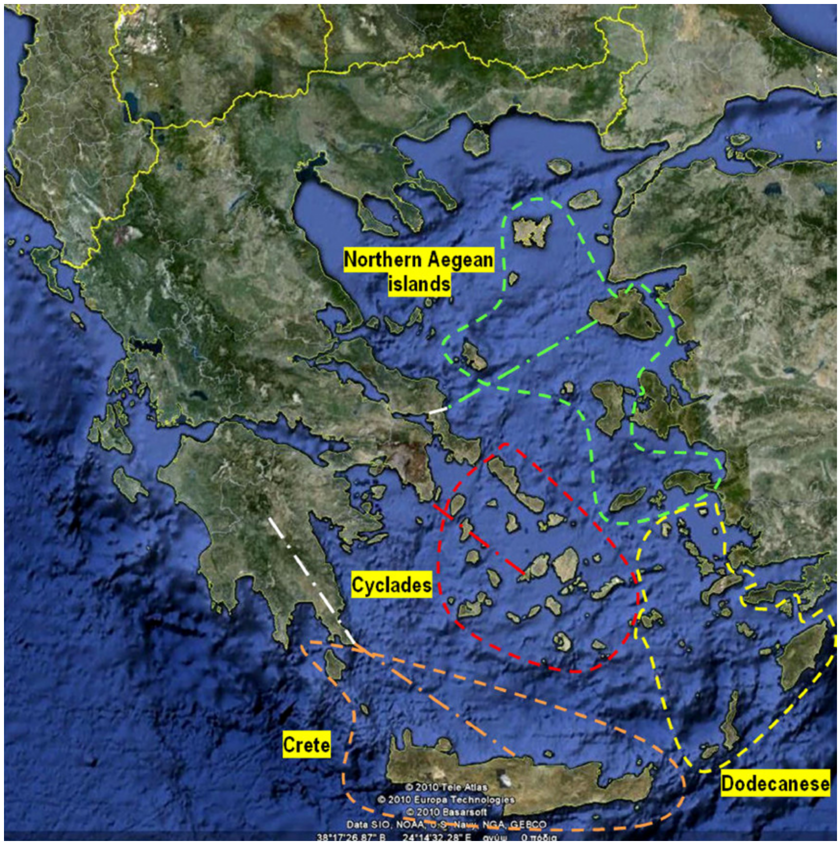

Fig. 4. Specification of four clusters of Greek islands and their interconnection schemes.

its base year's emissions. CO_2 is the main GHG pollutant and is produced in large quantities by the electricity generation. Above 50% of country's total CO_2 emissions originates from the power sector revealing the great importance and necessity to include them in the long-term electric system planning.

According to the EU's environmental policy, Greece has also the obligation to reduce the SO_2 and NO_x emissions which are responsible for the acidification and eutrophication phenomena, to a given limit (emission ceiling) after 2010 onwards. SO_2 and NO_x are produced by the conventional power stations combusting lignite and oil products representing the next most significant pollutants after CO_2.

Greece has also to comply with the recently agreed EU targets, known as 20–20–20 by 2020, referring to the further reduction of GHG emissions, the drastic expansion of the RES share in the final energy consumption and the adoption of efficient energy saving measures. EU pays great attention to the further development of RES and Greece's individual target is set to 18% in final energy consumption. Recently, the Greek Ministry of Environment, Energy & Climate Change (MEECC) readjusted this target to the more ambitious value of 20%, while RES share in electricity generation is set to reach 40% in 2020.

All above obligations and targets are taken into consideration in this study and are included into the long-term energy planning by appropriate mathematical formulations.

2.3. Specific characteristics

The Greek power system has several structural weaknesses and peculiarities, while facing a significant number of problems that are going to be shortly described below.

The geomorphology of Greece comprising a large number of islands and an extensive mountain chain accompanied by unevenness in population allocation makes the placement of new power plants, especially of RES units a complicated task, while hampering the development of the necessary electric grids. There is also a certain shortage of appropriate infrastructures and adequate electricity grids capable to welcome new investments on RES, this being a significant reason for their very low participation in the power mix.

Hence, the Greek electricity system has not a united structure as it consists of the mainland and separate insular grids. This status impedes its integrated management and causes many technical, economic and environmental implications. As already mentioned, the Greek power system is strongly coupled to domestic lignite which has two severe disadvantages: a low calorific value and high emissions of CO_2, SO_2, NO_x and particulate matters. The pollution problems become even greater because the majority of lignite power plants are old units with low electrical efficiencies. On the other side, the insular power sector is vulnerable and dependent on oil prices and very high generation costs, while it does not allow for the large exploitation of RES.

Furthermore, the Greek power sector suffers from the disproportionate distribution of power plants in relation to the zones of major electricity demand. The large energy centers are located in Northern Greece while the heavy consumers are concentrated in South and especially in the greater Athens area in Attica.

The Greek power supply system also suffers from significant imports of expensive fossil fuels and overpriced electricity. Furthermore the annual demand curve presents very sharp peak loads in summer time that last for only a few hours and cause a lot of problems in system's stability.

All these problems, accompanied by the continuing rise of electricity demand, the increasing fuel prices and the necessary compliance with climate, energy and environmental targets set by the EU, should be taken into consideration in the energy planning of the Greek power sector.

3. Methodological approach

The strategic electricity planning presented in this study is implemented by developing and using a dynamic, long-term, national energy model adapted to the Greek power sector considering jointly the mainland and the insular electric systems. The energy model is a pure engineering model which adopts the bottom–up approach including significant amount of details and analytical data while covering a lot of parameters and dimensions of the examined problem. The energy model used follows the systemic approach considering the individual power plants as elements of energy forms' systems that are subsystems of greater structures like mainland and insular electric systems. At the higher level of aggregation these systems comprise the entire Greek power sector.

The scope of this long-term energy planning model is the determination of the optimum mix of energy sources as well as the combination of electricity generation technologies in order to satisfy future demand and ensure all specified constraints. It can be characterized as a traditional least cost energy model which encompasses some features of integrated resource planning like the environmental costs and the topic of interconnections.

It is a deterministic optimization model acting mainly as prescriptive model which belongs to the Mixed Integer Linear Programming category problems. The objective is the calculation of the net present value (NPV) of total costs of electricity generation during the given period. The cost objective function comprises a series of various cost categories like: annualized investment, fixed and variable operation and maintenance (O&M), fuel, GHG emission allowances purchase costs plus the cost of imported electricity and of course the cost of interconnections' development. It is clear that the sum of the discounted costs of electricity generation is to be minimized.

The electric interconnection of Greek islands to the mainland constitutes the core of the present study. Thus, a special modeling effort is given to simulate and integrate this capability into the long-term energy planning. The enormous number of Aegean islands is grouped into four large clusters representing their geographical specification, coverage and proximity. So, according to the existing administrative districts, we consider the insular clusters of Crete, Cyclades, Dodecanese and Northern Aegean islands as depicted in Fig. 4.

The basic concept behind the modeling of each interconnection option lies in its simulation through the usage of two virtual power plants of which the first one represents a unit located and generating electricity in mainland while the second one corresponds to a power unit operating in the insular cluster at the other side of the electric bond. The underlying rule does not allow the synchronous transfer of electricity in both directions.

Under this framework, the energy model decides on the necessity and feasibility of the interconnection between each insular cluster and the mainland system by providing as a result the appropriate start time of the interconnection as well as the most suitable size of the submarine cable to be installed. In more detail, the mathematical model may choose among three predefined types of submarine cables of different size (see Subsection 4.3) which build the interconnection capacity. The interconnection can be expanded through the installation up to three submarine cables within the planning horizon, with all cables being of the same size. The capacity of the interconnection comes up as the outcome of the least cost optimization of the problem and is determined by the most profitable extent of RES penetration, mainly of wind energy in each insular cluster. Obviously, the size of the interconnection regulates the amount of electricity that can be canalized between the insular cluster and the mainland. Major concern here is to bring 'clean' energy to the mainland through the RES exploitation in Aegean islands contributing to the coverage of its base power loads, while alleviating the unprofitable operation of insular electric systems through cheaper electricity generated in central system.

The only exception is the Dodecanese islands which are considered to continue operating as isolated electric systems, because interconnection in this case is not a priori a cost viable and efficient solution.

Based on 2nd Greek National Allocation Plan (NAP), we make the hypothesis that the free allocated emission rights can be transferred over the extended period 2009–2020 and also be exchanged among all units owned by the same power company. This approach helps to discover the power system's behavior against the future variations of EU allowances (EUA) price with respect to the economically beneficial capacity expansion planning of the electricity supply sector.

The objective function is subject to a variety of constraints which express economic, technological, environmental and legislative aspects. The constraints are structural parts of the elaborated model which represent in mathematical relations, the conditions, needs, capabilities and obligations of the Greek power system. Shortly, we mention the categories of the involved constraints:

- the satisfaction of annual electricity and peak power load demand
- the maximum penetration potential of each energy source and its associated technology
- the technical constraints of a power plant like minimum construction size and technical minimum of operation
- the stability of the electricity grid system due to extremely large penetration of RES both in mainland and insular sector
- the future natural gas availability
- the automatic retirement of no longer profitable power plants
- the maximum potential of hydropower plants
- the RES penetration target in electricity generation set by EU and MECCC
- the KP target for the abatement of GHG emissions
- the emission ceilings for acidification pollutants
- the development, size and operation of interconnections.

All the above constraints affect significantly the least cost objective function and so the outcome of the capacity expansion planning of Greek power sector.

The optimization energy model contains a large number of variables, continuous, integer and binary through which the necessary quantities are calculated and the expansion pattern of the power system is formulated. Continuous variables represent the power plant capacity, the interconnection size, the amount of electricity imports, the retired capacity, the power delivered by every power unit in each segment of the load duration curve (LDC), the reallocated GHG emission allowances, the purchased GHG emission rights, etc. Integer variables express the number of submarine cables of predefined size needed to construct the interconnection line between the insular cluster and the mainland. Binary variables refer to the decision to install or not, as well as to withdraw or not, a power plant, to operate it in a year or not, to determine the direction of electricity transfer through the interconnection etc. In addition, there are auxiliary variables which help to state important quantitative aspects of the electricity system, like electricity produced, CO_2 emissions, various cost categories, emission factors, etc.

Table 1
Technical characteristics of candidate power plants.

Type of power plant	Load factor[a] (h)	Technical minimum[b] (%)	Electric efficiency[c] (%)	Lifetime[d] (yrs)	Lead time[e] (yrs)	CO_2 emission factor[f] (tn/MWh)
Lignite	8000	50	42.3	40	4	1
HFO	7500	35	43	35	2	0.648
LFO gas turbine	7500	10	36	25	2	0.732
NGCC	5800	60	57.5	35	3	0.344
Small hydro	2400	0	85	60	3	0
Large hydro	2000	0	85	100	7	0
Wind park (onshore)	2600	0	40	20	1	0
Wind park (offshore)	3300	0	40	20	1	0
PV	1200	0	15	25	2	0
Geothermal	7000	0	15	30	2	0
Biogas CHP	7500	10	40	25	2	0
HFO ICE	6000	45	47.6	20	1	0.585
LFO ICE	6000	45	47.6	20	1	0.554

[a] Source: [10–21].
[b] Source: [16,22].
[c] Source: [10,16,23–26].
[d] Source: [10,16,27].
[e] Source: [10,16,27].
[f] Source: [10].

The energy model used in present analysis is developed in the environment of GAMS (General Algebraic Modeling System) modeling language and for its solution, the GAMS/CPLEX (branch and cut algorithm) solver is used. The full model consists of 169,235 continuous variables (main and dependent) and 4460 discrete variables (integer and binary) while it encompasses 145,857 mathematical relations (constraints and supplementary equations). The least cost energy planning model is accompanied by a useful software named LEP^{2}SIS^2 (Long-term Energy Planning in Power Sector Information Support System) which has a Microsoft Excel based graphical user interface including many applications and tools in order to facilitate even the non sophisticated users to easily insert and edit data, to develop scenarios and to obtain, study and compare results.

4. Data

4.1. General

The scenarios analyzed below share the same data and assumptions in order to secure the comparability of results. To solve the problem, we use a plethora of data deriving from recent bibliography and multiple technical reports.

Table 2
Economic data for candidate power plants.

Type of power plant	Investment cost[a] (€/MW)	Fixed O&M cost[b] (€/MW)	Variable O&M cost[c] (€/MWh)
Lignite	2,000,000	60,000	1
HFO	930,000	65,000	1.5
LFO gas turbine	500,000	23,000	2
NGCC	600,000	26,000	1.5
Small hydro	1,600,000	32,000	0
Large hydro	2,000,000	40,000	0
Wind park (onshore)	1,400,000	28,000	0
Wind park (offshore)	2,200,000	44,000	0
PV	3,000,000	30,000	0
Geothermal	2,500,000	75,000	0
Biogas CHP	1,600,000	150,000	6
HFO ICE	1,100,000	56,000	7
LFO ICE	1,100,000	56,000	7

[a] Source: [7,10,16,17,28–35].
[b] Source: [7,10,32,35–40].
[c] Source: [8,30,36–41].

4.2. Power plants

The capacity expansion planning of the Greek power sector considers three general types of power plants, the candidate (new), the existing (old) and the scheduled power units. As scheduled, we consider the power plants that have been already decided by the PPC ant the other private companies to be constructed in the future stepping to 2020. The participating power plants involve various technologies like: conventional and IGCC lignite power stations, HFO conventional power station, LFO gas turbine power plant, HFO and LFO internal combustion engines (ICE), natural gas turbine power station, natural gas combined cycle (NGCC) power plant, mini, small and large hydroelectric stations, wind farms, PV parks and geothermal power plants plus biogas combined heat and power (CHP) plant. Each power technology as a potential investment is accompanied by a significant number of data concerning technological, economic and environmental aspects. Tables 1 and 2 present only the techno-economic data of the most widespread power technologies appearing also in the results of both scenarios.

All types of power technologies and energy sources producing electricity have specific limits in their penetration rate in order not to bear unrealistic and impossible expansion plans. According to recent and expected records in Greece, reasonable constraints are imposed for the maximum RES penetration, the imports of fossil fuels and the imported electricity on an annual basis.

Regarding old power stations, there is an already elaborated plan for the gradual retirement of 1.8 GW of lignite power plants, 537 MW of natural gas power stations and 750 MW of HFO power plants in the near future in the mainland system. In islands, the total capacity of HFO and LFO power stations to be retired is 700 MW and 511 MW, respectively.

On the other hand, the energy planning procedure of the Greek power sector takes into account the scheduled addition of new capacity concerning 2 GW of NGCC power plants in mainland and 702 MW in Crete, 1050 MW of lignite power plants, 631 MW of large hydropower stations and the installation of some new oil ICE in islands.

4.3. Interconnection

To implement the interconnection of each insular cluster to the mainland, there are available three types of submarine DC cables of different capacity: 250 MW, 350 MW and 500 MW presented in Table 3. The selection of these particular types is based on a relevant study [7] and takes also into account the estimated electricity

Table 3
Costs of interconnection equipment [43,44].

Equipment		Cost	
Submarine DC cable	250 MW	443	10^3 €/km
	350 MW	558	10^3 €/km
	500 MW	730	10^3 €/km
Submarine AC cable	140 MVA	700	10^3 €/km
	280 MVA	800	10^3 €/km
Overhead line	150 kV	120	10^3 €/km
AC/DC converter station		80	10^3 €/MVA

Table 4
Electricity and peak load demand for the mainland system [45,46].

	Electricity demand (GWh)	Peak load (MW)
2009	52,800	9830
2010	53,800	10,400
2011	54,970	10,650
2012	56,100	10,850
2013	57,200	11,100
2014	58,270	11,300
2015	59,620	11,550
2016	61,100	11,850
2017	62,600	12,100
2018	64,130	12,400
2019	65,700	12,700
2020	67,320	13,000

demand forecast and the wind energy potential per insular cluster. The submarine cables belong to DC technology as being the best economic and technological option taking into account that the distance of the insular clusters to the central grid is above 100 km [7,42]. The implementation of each interconnection requires the installation of AC/DC and DC/AC converters on both sides, submarine AC cables for the inner interconnection of the islands belonging to the cluster, the overhead lines on land and the rest equipment needed like filters, transformers etc. Table 3 presents the corresponding costs according to which the final investment capital of each interconnection is calculated.

4.4. Electricity demand forecast

The electricity demand forecast used in this study has recently been modified and updated due to the economic crisis and the expecting decrease in future consumption. The evolution of demand for the mainland system is based on the scenarios developed by the Hellenic Transmission System Operator (HTSO) and the estimations of the former Council of National Energy Strategy (see Table 4) adopting the baseline trend. Concerning the Greek islands' electric system, the task is much more complicated because of the lack of credible estimates. Thus, forecasts rely on a recent report of the former Greek Ministry of Development and relevant records from the PPC which is the exclusive operator of the islands' electric grids (see Table 5).

Furthermore, in order to ensure reliable electricity supply in the future, it is assumed a 20% reserve margin according to the standard practice [47].

Focusing on the annual demand of electricity, it is simulated by the corresponding LDC. In the present analysis, five general patterns of LDC's are created, one for the mainland grid and four different ones for each cluster of islands properly modified for every year of the examined period.

Table 6
Fuel prices evolution.

Fuel	Unit	Quadrennium		
		2009–2012	2013–2016	2017–2020
Lignite	€/tn	13.4	13.4	16
Natural gas	€/1000 m^3	402.4	424.8	453.4
HFO	€/m^3	466	614	651
LFO	€/m^3	554	729	774

Table 7
Evolution of EUA price.

Years	2009–2010	2011–2012	2013–2016	2017–2020
Price (€/tn)	15	20	28	37

4.5. Fuel and EUA prices evolution

In the present study, we consider the evolution of fuel prices according to national and international estimations choosing always the base case. Lignite as a domestic energy source is not affected by variations in the international market and follows a conservative trend in its price as shown in Table 6.

The cost of HFO and LFO is only important for insular regions and it is directly connected to global oil prices fluctuations. In order to estimate the future prices of oil products, we use the current data from PPC [29,48] adapted to the recent baseline scenario developed by the United States (US) Energy Information Administration (EIA) (see Table 6) [49,50].

Regarding natural gas, the baseline scenario adopts the forecast of US EIA which partially correlates the natural gas price evolution with the oil price but giving great attention to the effect of future increasing consumption of natural gas.

The progress of EUA price is presented in Table 7 revealing a continuous rise of their purchase cost leading to overdoubling in the last 4 years of the planning horizon. The EUA price trend represents an altered version of the most possible scenario before the

Table 5
Electricity and peak load demand for the insular systems [18].

Year	Crete		Cyclades		Dodecanese		Northern Aegean islands	
	Demand (GWh)	Peak load (MW)	Demand (GWh)	Peak load (MW)	Demand (GWh)	Peak load (MW)	Demand (GWh)	Peak load (MW)
2009	3026.6	630	607.6	183	1165.5	310	727.3	167
2010	3125.9	680	632.9	199	1205.9	334	743.0	178
2011	3252.1	713	660.7	208	1253.8	349	760.9	183
2012	3394.3	749	688.6	218	1299.0	364	777.9	187
2013	3519.2	780	718.5	228	1350.4	380	796.7	193
2014	3630.5	810	746.8	238	1395.7	390	812.9	197
2015	3774.8	848	779.3	249	1447.5	401	832.6	203
2016	3924.7	889	813.9	262	1504.8	415	853.6	210
2017	4092.8	932	849.7	274	1561.9	428	874.7	215
2018	4239.0	973	886.4	288	1618.6	442	895.8	222
2019	4404.4	1020	924.3	302	1679.5	457	917.0	229
2020	4568.6	1067	963.5	317	1739.7	473	938.4	236

Table 8
Natural gas reserves for the power sector up to 2020 [55,56].

Year	Natural gas volume (million m^3)	
	Total	Power sector
2009	3373	2085
2010	4200	2968
2011	4560	3233
2012	4920	3489
2013	5280	3734
2014	5640	3968
2015	6000	4193
2016	6360	4406
2017	6720	4610
2018	7080	4803
2019	7440	4986
2020	7800	5158

economic crisis which has been modified according to the new estimations made by the specialized company Pointcarbon [51–54].

4.6. Natural gas availability

The scenario about the natural gas availability for the power sector needs is shaped according to the forecast data of Public Gas Corporation [55]. Table 8 reveals the prospective adequacy of natural gas reserves due to the deployment of the natural gas pipelines around and through the Greek territory as well as the anticipating construction of new terminals accepting liquefied natural gas.

4.7. Emission targets

As already mentioned, Greece has the obligation to mitigate GHG emissions under the KP accordance. In the present analysis, we specify this overall target to the power sector by making the realistic hypothesis that the amount of GHG emissions is identical to the amount of CO_2 emissions, since CO_2 is the dominant GHG in the power sector possessing a share above 99.5% [57]. Taking into account the CO_2 emissions in the base year and their recorded and estimated trends, we assume an upper bound for the allowable increase equal to 35%, reflecting the expected greater contribution of electricity generation in total emission reduction.

Regarding NO_x and SO_2 emission ceilings, they are adjusted to the power sector by taking into account the historic share of the acidification pollutants emitted by the power utilities over the country's total (see Table 9).

4.8. Other data and assumptions

The planning horizon of this study is set to 12 years up to the limit year 2020 for the EU obligations. For this period there are plenty of credible data and predictions concerning future electricity demand and prices evolution.

The discount rate influences the choice of the least cost solution and affects greatly the whole economic appraisal of the capital intensive investments such as power plants. The discount factor chosen for the following analyses is set equal to 6%, which is a typical value in the EU and many other developed countries [60,61].

Table 9
SO_2 and NO_x emission ceilings in power sector [58,59].

Pollutant	Emission ceiling (kt)	
	Power sector	Total
SO_2	366.1	523
NO_x	103.2	344

Table 10
Progress of interconnection to mainland per insular cluster (MW).

Year	Crete	Cyclades	Northern Aegean islands
2012	500	350	0
2013	0	0	350
2014	0	0	0
2015	0	0	0
2016	0	0	0
2017	0	0	0
2018	0	0	0
2019	0	0	0
2020	500	0	0
Total capacity	1000	350	350

According to the 2nd NAP for the period 2008–2012, Greek power utilities have been granted with specific free GHG emission allowances which are allocated per power plant and can be grouped per owning company. Their total amount for the period concerned 2009–2012 is equal to 183.7 Mt while for the new entrants, there is a dedicated bank of 10 Mt.

5. Results

5.1. Scenarios

In order to investigate the feasibility of islands' interconnection and the effect on RES development, we developed two scenarios. A baseline scenario (BS) which does not include the option of interconnection and considers the present status of isolated operation of insular electric systems to continue and the interconnection scenario (IS) giving the islands the possibility to connect to mainland under the prospective of least cost expansion and operation of the Greek power sector.

5.2. Islands' interconnection

Table 10 presents the results of the IS. It can be seen that the optimization of the Greek power sector implies the interconnection of all candidate insular clusters to the mainland system. Crete is connected with a submarine cable of 500 MW in 2012 and at the end of the period another similar cable is added upgrading the interconnection capacity to 1000 MW. In 2012, Cyclades are also connected with a 350 MW cable while, the cluster of Northern Aegean islands follows next year with a similar cable.

The comparative evaluation of the two scenarios from the economic point of view shows that interconnection results in a lower generation cost compared to the baseline case. It is namely shown that the objective function of the developed model, representing the NPV of the cumulative generation cost for the planning period is equal to 39.5 billion € for IS and rises up to 40.7 billion € for the BS.

The following paragraphs present on a comparative basis the two scenarios BS and IS by looking in more detail on their differences in the installed capacity, the electricity mix and other important characteristics of the Greek power sector.

5.3. Installed capacity

Taking into account the existing power plants, the scheduled entrance and the retirements of power units, the IS shows an expansion of the Greek power sector to 27 GW in 2020, by 1.8 GW greater than in the BS. This increase is due to the extra development of wind parks in Greek islands after their interconnection, summing up to 2723 MW (see Tables 11 and 12).

As seen in Table 13, wind energy presents by far the highest upward trend compared to the mediocre 1 GW in 2008 and the

Table 11
Evolution of installed capacity in mainland, insular and whole power system per scenario (MW).

Year	Mainland system		Insular system		Total	
	BS	IS	BS	IS	BS	IS
2008	12,961	12,961	1807	1807	14,768	14,768
2009	13,461	13,461	2134	2145	15,595	15,606
2010	14,559	14,559	2221	2226	16,780	16,786
2011	15,576	15,587	2376	2370	17,953	17,957
2012	15,430	15,911	2761	2658	18,191	18,569
2013	16,895	17,389	3013	2952	19,908	20,341
2014	17,405	17,915	2961	3097	20,365	21,011
2015	18,217	18,744	3508	3907	21,725	22,651
2016	20,280	20,812	3456	4126	23,736	24,938
2017	21,274	21,826	3418	4345	24,692	26,170
2018	21,326	21,874	3331	4535	24,657	26,409
2019	20,958	21,196	3366	4794	24,324	25,990
2020	21,956	22,182	3197	4794	25,153	26,976

Table 12
Evolution of installed capacity of each insular cluster per scenario (MW).

Year	Crete		Cyclades		Dodecanese	Northern Aegean islands	
	BS	IS	BS	IS	BS and IS	BS	IS
2008	925	925	236	236	391	255	255
2009	1036	1043	322	326	467	310	310
2010	1055	1058	350	353	495	323	320
2011	1065	1068	367	357	621	330	325
2012	1280	1197	371	340	674	450	447
2013	1439	1292	393	390	748	457	522
2014	1305	1248	414	440	811	458	597
2015	1827	1883	432	515	831	443	678
2016	1840	2005	436	605	741	455	775
2017	1692	1993	530	720	725	471	906
2018	1705	2139	409	699	729	488	968
2019	1719	2271	414	830	718	515	974
2020	1741	2444	395	809	733	329	808

largest share in total installed capacity. Under the interconnection status, this share grows even more going to 44.4% with the final wind capacity reaching 12 GW, by 2 GW higher than in the baseline case. This tremendous penetration reveals the positive effect of the interconnections which favor the high exploitation of the abundant wind potential of Greek islands.

The other RES make also a substantial and similar progress in both optimization scenarios. Hydro capacity increases by 1 GW stemming from both small and large hydropower plants and reaches in total 4.3 GW in 2020. The same happens for biogas CHP plants which come up to 539 MW. In the case of PV installations, their total capacity does not exceed 700 MW, which is the minimum national target to be attained. In the IS, geothermal energy

Table 14
Evolution of installed capacity of fossil fuel per scenario (MW).

Year	Lignite		Natural gas		Oil products	
	BS	IS	BS	IS	BS	IS
2008	5288	5288	2908	2908	2331	2331
2009	5288	5288	2908	2908	2555	2565
2010	5288	5288	3343	3343	2555	2565
2011	4800	4800	3845	3845	2649	2659
2012	4500	4966	4053	3903	2039	2019
2013	4375	4841	5003	4703	1739	1719
2014	4075	4541	5003	4703	1595	1575
2015	4075	4541	5515	5215	1540	1520
2016	5185	5651	5617	5317	1332	1312
2017	5185	5651	5617	5317	1227	1132
2018	4285	4751	5617	5317	1092	997
2019	3675	3841	4909	4609	1086	966
2020	3675	3841	4909	4609	882	737

reaches 315 MW being slightly higher than in BS (284 MW) because of the additional installations implemented in insular grids. Totally, all RES with wind energy at head, count up to a very high share in both scenarios showing the great potential of Greece to promote sustainable ways of producing electricity. This potential can be further enhanced by the development of interconnections of islands to the central grid.

In both scenarios, the installed capacity of lignite power stations records a significant drop of about 1.6 GW between 2008 and 2020, mainly because of the scheduled retirement of old units (see Table 14). The final capacity is higher in the IS due to the entrance of a new larger lignite power plant. An impressive decline is recorded in the case of oil capacity which does not exceed 1 GW in 2020, showing an over 60% decline because of both, the elimination of oil power stations in mainland and their significant abandonment into islands' electric systems. The existence of interconnections inhibits further the addition of new oil power plants after 2012 causing their total capacity to drop to 737 MW installed mainly in Dodecanese (see Table 14). Natural gas units present a significant installed capacity equal to 4.9 GW because of the already scheduled NGCC power plants, although the electricity produced is relatively low because of the high price of natural gas. The difference between the two scenarios refers to the postponement of the installation of 300 MW NGCC power plants after the interconnection of Crete.

5.4. *Electricity generation*

The pair of graphs in Fig. 5 illustrates the evolution of electricity generation mix for the entire Greek power sector under the two different scenarios. The total amount of electricity produced is determined according to the forecast demand and other tech-

Table 13
Evolution of installed capacity of RES (MW).

Year	Wind energy		Large hydro		Small hydro		Biomass/Biogas		Solar energy		Geothermal energy	
	BS	IS	BS	IS	BS	IS	BS	IS	BS	IS	BS	IS
2008	1016	1016	3016	3016	159	159	39	39	12	12	0	0
2009	1619	1619	3016	3016	159	159	39	39	12	12	0	0
2010	2285	2285	3016	3016	188	182	89	89	12	12	5	5
2011	2922	2922	3333	3333	238	232	139	139	12	12	15	15
2012	3634	3722	3362	3362	288	282	189	189	100	100	25	25
2013	4347	4639	3647	3647	338	332	264	264	150	150	45	45
2014	5053	5558	3647	3647	388	382	339	339	200	200	65	65
2015	5761	6547	3647	3647	438	432	414	414	250	250	85	85
2016	6572	7634	3647	3647	488	482	489	489	300	300	105	105
2017	7383	8797	3647	3647	538	532	539	539	400	400	155	155
2018	8183	9870	3647	3647	588	582	539	539	500	500	205	205
2019	8977	10,905	3647	3647	638	622	539	539	600	600	252	260
2020	9858	11,965	3647	3647	658	622	539	539	700	700	284	315

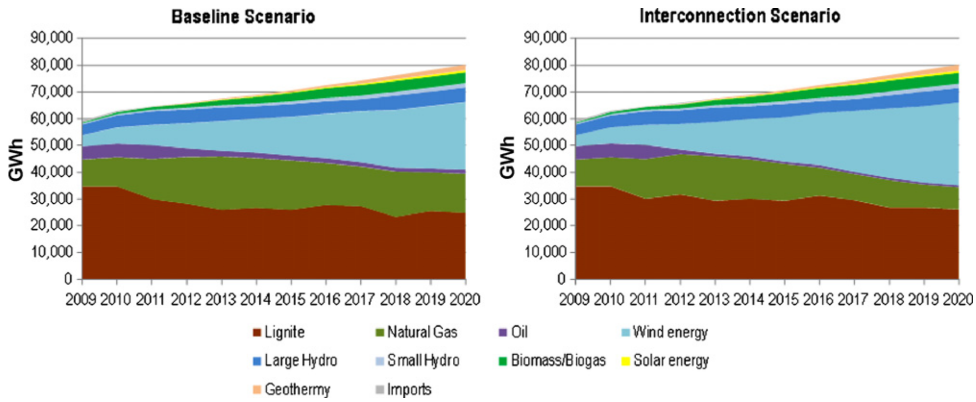

Fig. 5. Evolution of electricity generation mix in the whole power sector per scenario.

nical data and relevant constraints and reaches 80.2 TWh in 2020. Wind energy clearly possesses a prominent role with a continuously rising share which in IS goes beyond 30 TWh in 2020, being higher by 5 TWh compared to BS. It is interesting to notice that in the last 2 years the electricity generated from wind farms exceeds the production of lignite power units. The final share of wind energy in the IS reaches 38.4%, higher by about 7% compared to BS, mainly because of the extra capacity of wind parks in Greek islands.

The production of other RES technologies is about the same in both scenarios, with hydroelectric stations producing 7 TWh, biogas units 4 TWh and PV's 0.8 TWh, in 2020. Only geothermal plants present a higher production by about 10% in the IS, reaching 2.2 TWh in 2020.

Obviously, the rise in the share of RES goes along with the decline of fossil fuels' contribution, in both scenarios. Nevertheless, it is worth noticing that the interconnection of islands results in an impressive reduction in the share of natural gas in the electricity mix, whereas the drop is less in the case of lignite power plants, which are used in order to cover part of the electricity demand of the interconnected islands.

Similarly, the usage of oil products declines from 5 TWh to 1.5 TWh and 0.9 TWh for BS and IS, respectively. This small amount of oil production corresponds almost exclusively to the not interconnected isolated system of Dodecanese.

The pair of graphs in Fig. 6 fully confirms the tremendous penetration of RES, especially of wind energy, in electricity generation in both scenarios. In BS the RES share increases from around 15% in 2009 to almost 49% in 2020, while in IS it is further boosted to the ambitious level of 56%. The optimization process verifies the unbiased trend of the Greek power system towards renewable and sustainable ways of producing power at an extent that is significantly overlapping the target set by MEECC for 2020.

Fig. 7 presents the mix of electricity generation in the mainland system with and without interconnections. The new interesting point here is the electricity inflow from Greek islands after the development of interconnections. The central grid accepts a significant amount of electricity coming from the three interconnected insular clusters and summing up to 2.5 TWh at the end of the examined period. It should be noticed that 95% of the electricity inflows originate from Cyclades and Northern Aegean islands. The small contribution of Crete is due to its much higher local demand.

The comparison of the two diagrams reveals a slight increase in the sum of electricity generated in IS which originates from electricity imports via the interconnections and the small rise of lignite power plants' usage. In fact, there is an exchange of electricity loads in both directions in different segments of the LDC's in order to be allocated in the most cost effective way. The mainland system acts as a consumer of the electricity generated by RES in insular regions in order to cover a part of its base loads and also as a producer satisfying intermediate and peak power loads in islands. So, this small rise in mainland's electricity generation can be seen as the combinatorial outcome of electricity imports and exports through the existing interconnections.

Fig. 8 presents the shift to a radically new era in Crete's electric system after the installation of the 500-MW submarine cable followed by an identical additional cable in 2020. Wind energy is strongly favored reaching in IS to a total production of about 3.7 TWh of electricity in 2020 which is four times higher compared to BS.

Crete behaves like a net consumer of electrical energy produced in mainland. At the beginning, imports of electricity represent 75% of total electricity consumption in the island. Progressively, imports' volume decreases as wind energy is further exploited and is limited to 30% of total consumption. As it is clear from the IS diagram in Fig. 8, Crete takes the full advantage of both, the stable electricity produced in mainland's lignite units and the clean electricity generated by local wind parks.

Another noteworthy element of the future evolution of Crete is the elimination of oil power stations after the year 2012, in both scenarios. In BS, because of the entrance of natural gas which gradually reaches 4.4 TWh, representing almost 80% of total electricity generation. In IS, the role of natural gas is significantly restricted to 0.2 TWh because the interconnection offers a more attractive and cost beneficial way to supply electricity originated from the mainland.

In Cyclades also, the most prominent effect of the interconnection to central grid is the remarkable penetration of wind energy generating 1.8 TWh in 2020 and representing 70% of total input in production (see Fig. 9). This volume is 20 times higher than the actual production and 6 times higher compared to BS.

In BS, a significant amount of electricity is produced by geothermal plants summing up to 730 GWh in 2020 (62% share of the local power mix) and characterized by a high utilization factor and their ability to serve base loads. A side effect of this large wind energy deployment after the interconnection is the delay and shrinkage of this geothermal energy because of its higher investment cost.

As expected, the promotion of RES is significantly restricting the contribution of oil power stations, in both scenarios. In BS, geothermal energy plays a major role to meet base load demand, while in IS the interconnection makes Cyclades fully independent from oil products by taking advantage of the imported electricity from mainland and the local dominance of wind power.

The Cyclades interconnection has also a double role. In the beginning it serves the local insular consumption by 'pumping' the necessary quantities of electricity produced in the mainland. Afterwards, as wind energy advances, the cluster of Cyclades becomes

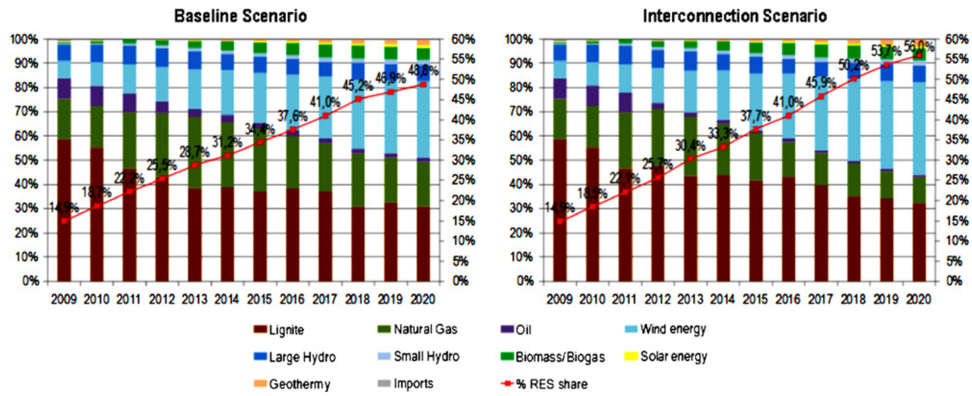

Fig. 6. RES share in electricity generation per scenario.

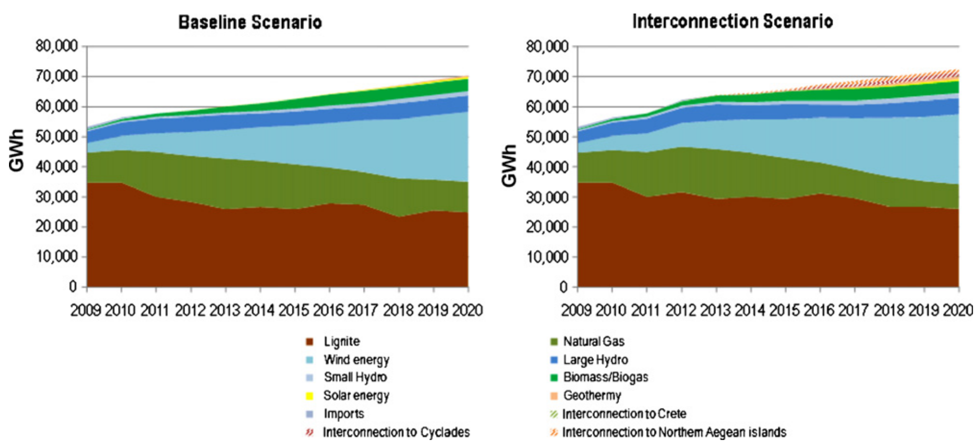

Fig. 7. Evolution of electricity generation mix in mainland per scenario.

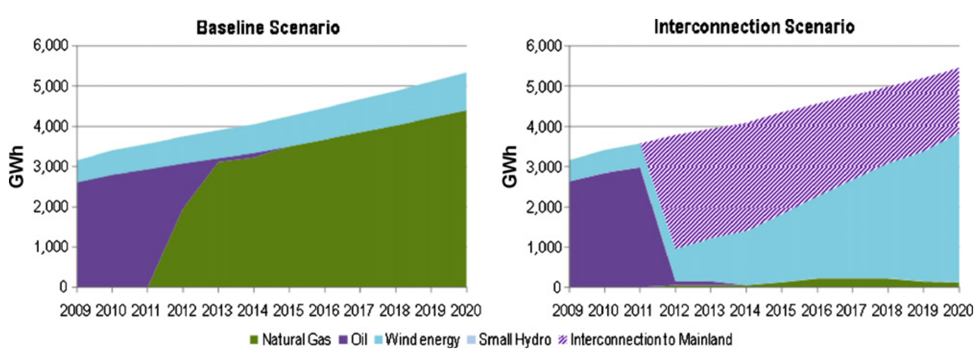

Fig. 8. Evolution of electricity generation mix in Crete per scenario.

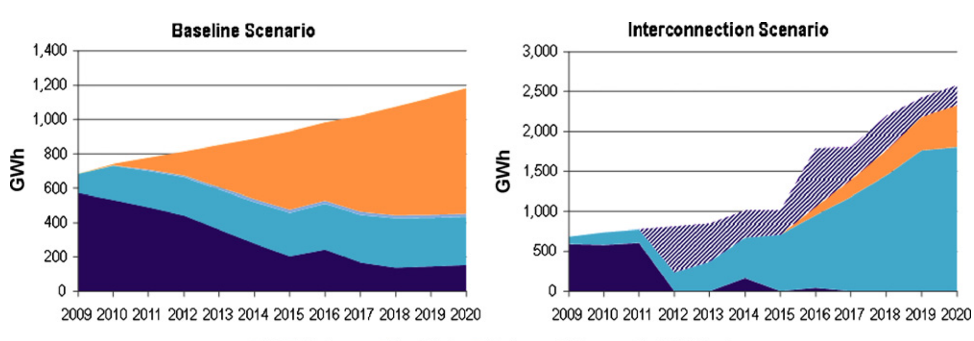

Fig. 9. Evolution of electricity generation mix in Cyclades per scenario.

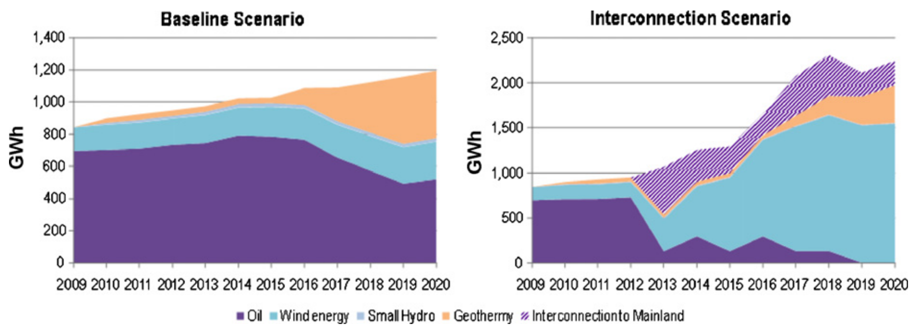

Fig. 10. Evolution of electricity generation mix in cluster of Northern Aegean islands per scenario.

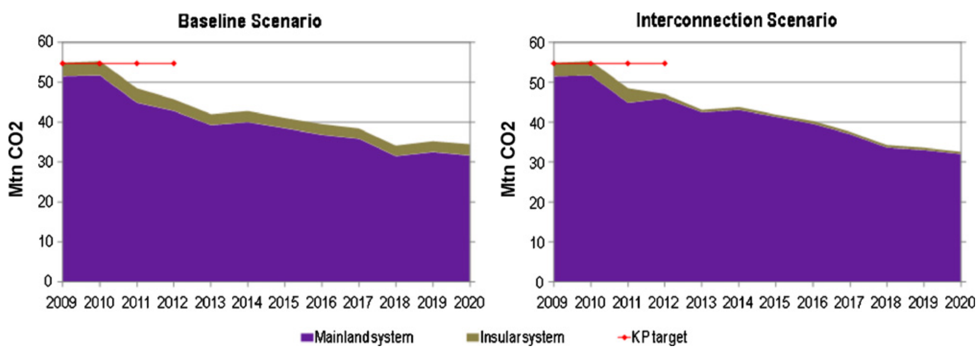

Fig. 11. CO_2 emissions evolution per scenario.

a supplier of sustainable electricity to the central grid. This second role makes the level of electricity generation in the second graph to be higher because now the Cyclades' electric system satisfies part of the total Greek system's demand. The interconnection offers both economic and environmental benefits to the local community of Cyclades and to the whole Greek power sector.

The pair of graphs in Fig. 10 illustrates that the evolution of electricity generation mix of Northern Aegean islands in both scenarios, and especially the transition from the isolated to the interconnected mode is quite similar compared to the complex of Cyclades.

In IS, wind energy acquires again a dominant role by generating 1.5 TWh of electricity in 2020 which is 10 times larger from the actual production and 6 times higher compared to BS. In both scenarios, geothermal plants produce a significant amount of electricity which under the interconnection state is constrained by about 20% due to its substitution by wind energy.

Regarding oil power plants, the BS shows a 25% decrease in their contribution to cover electricity needs due to the rising production from geothermal energy. The combinatorial effect of the large RES production and the imports of electricity from the mainland under the IS, drives to a vertical fall in 2012 and finally to the full withdrawal of oil units after 2019.

Northern Aegean islands constitute the second pylon of cheap and clean electricity delivered to the mainland grid, besides the Cyclades' complex.

5.5. Environmental effects

The Greek power system has been always characterized as highly polluting because of the large quantities of CO_2 emitted by lignite power plants. The diagrams in Fig. 11 reveal the striking abatement of CO_2 emissions which becomes greater in the case of interconnection due to the extra reduction achieved in islands. The CO_2 emissions decrease by 37.4% in BS and by 40.7% in IS up to 2020. Correspondingly, the CO_2 emission factor of the Greek power system is more than halved compared to actual values, dropping to 0.429 tn CO_2/MWh in BS and 0.407 tn CO_2/MWh in IS.

The significant CO_2 decline, which is common in the two scenarios originates from the great reduction of electricity production by lignite, the retirement of old power stations together with the high penetration of wind energy and of other RES. The further CO_2 abatement taking place in IS is explained through the extra boost of wind energy and the complete abandonment of oil power stations in the interconnected islands.

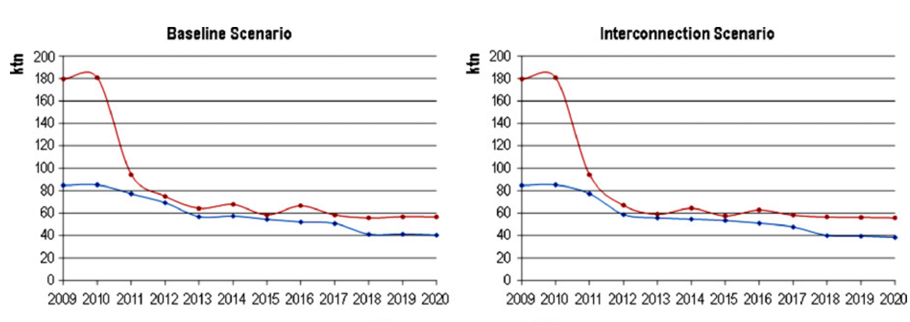

Fig. 12. NO_x and SO_2 emissions evolution per scenario.

It is clear that the Greek islands interconnection acts constructively to the whole Greek power sector combining the scope of cost minimization along with the environmental benefit of lower CO_2 emissions. Especially, the insular regions are being extremely favored as they become independent from the expensive and highly polluting electricity generation by HFO and LFO with consequent benefits to local communities, better living conditions, tourism reinforcement etc.

Fig. 12 shows the decreasing evolution of NO_x and SO_2 emissions following a similar route in both scenarios. NO_x emissions are cut back by 50% in the BS and by 55% in the IS. In the case of SO_2, the respective decline amounts to 68% and is almost the same in the two scenarios. The shift from lignite to natural gas explains the sharp drop in the first 3 years of the planning period.

5.6. Conclusions

The long-term electricity planning constitutes a flexible framework to assess and determine the expansion pattern of electricity production by selecting the optimum mix of energy sources and generation technologies under the prospect of total cost minimization. This paper examines the Greek power sector which has several particular characteristics and structural weaknesses. We have focused on two significant and interrelated issues concerning:

a) the extremely low penetration of RES in electricity generation despite the high potential of Greece, and
b) the dispersed number of islands corresponding to many individual isolated electric systems which are operating under non cost effective conditions.

This dual problem is a great challenge which can be effectively coped with the highly promising interconnection of Greek islands to the mainland system.

In this study, the traditional least cost electricity planning is extended through the incorporation of the interconnections development as a core element of the future expansion of the power sector. The developed energy model integrates the option of interconnections while taking into account all aspects and imposed constraints such as environmental protection and especially the abatement of climate change. The results obtained by the comparison of the two contrasting scenarios, reveal the significant contribution of the Greek islands' interconnection to the restructuring on a sound and cost effective basis of the whole power sector.

RES and especially wind energy are strongly favored as their penetration in the power generation mix exceeds the set target and is possible to reach 56% and thus, cover a significant portion of electricity demand. Almost 12 GW of wind power is installed due to the extensive exploitation of the high potential in Greek islands followed by hydro and geothermal energy advance. The existence of interconnections removes the obstacles concerning technical minima of local conventional power stations and the dynamic constraints of wind energy.

As far as the other conventional ways of producing electricity are concerned, they are expected to gradually reduce their contribution by at the same time alleviating the power system from their emissions and higher costs. Lignite power plants' utilization is compressed by 30% while oil usage in interconnected islands falls vertically by about 80%. The above changes in the electricity mix has the supplementary effect of the further abatement of CO_2 emissions, as well as of other pollutants like NO_x and SO_2.

Being the target of the present energy planning process, the development of interconnections results as the optimum solution succeeding in the curtailment of total electricity generation cost. Despite the increase in investment costs concerning further installation of wind parks and the construction of interconnections, the objective function presents smaller NPV. The electricity generation costs fall in all electric subsystems, with the most important savings taking place in islands due to the replacement of the costly HFO and LFO used in non-efficient small units of the isolated systems.

Conclusively, the interconnection of Greek islands to the mainland offers both economic and environmental benefits to the whole power sector contributing to its sustainable expansion and by further developing the high RES potential.

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